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Predicting albatross bycatch hotspots across the North Pacific Ocean

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Executive Summary

Bycatch threatens many seabird populations and remains a barrier to fisheries sustainability. Albatrosses are particularly vulnerable to bycatch in longline fisheries across the North Pacific due to their wide-ranging movements and attraction to fishing vessels. Identifying when, where and in which fisheries bycatch risk is greatest is crucial to prioritize monitoring and recommend targeted management interventions. Here, we collated >1,200 albatross tracks from eleven populations of three species (short-tailed, Laysan, and black-footed) in the North Pacific to provide an ocean-basin-scale assessment of bycatch risk. We overlaid species distribution model predictions of bird densities for each population and breeding stage with Automatic Identification Systems data on pelagic longline fishing effort and created indices of bycatch risk. Albatross distribution models had strong predictive power (mean [range] area under receiver operating characteristic curve: 0.91 [0.75-0.98]). We identified bycatch risk hotspots from pelagic longline fisheries in the central and northwest subtropical Pacific that occurred mostly during breeding (winter-spring); though the months with elevated risk differed according to population and fishing vessel flag state. Considerable (88%) overlap with pelagic longline fishing effort occurred in the High Seas where observer coverage is extremely low (<5%) and use of bycatch mitigation is variable. Three flag states (Japan, USA and Taiwan) were responsible for >90% of total risk. Our results indicate that improved monitoring and increased adoption of and compliance with best-practice mitigation measures in high-risk fleets would reduce future conflicts between fisheries and albatrosses.

We recommend the WCPFC-SC20:

- Prioritize increasing observer coverage of the longline fleets of Japan (particularly the small offshore fleet; 10-19 gross register tonnage) and Taiwan.

- Mandate adoption of best-practice seabird bycatch mitigation measures in all North Pacific longline fleets, particularly the fleets of the US, Japan and Taiwan, particularly in high-risk areas and seasons.

1. Introduction

Bycatch is a major threat to seabirds, including North Pacific albatrosses – black-footed *Phoebastria nigripes*, Laysan *P. immutabilis* and short-tailed *P. albatrus* albatrosses – all of which are listed by the Agreement for the Conservation of Albatrosses and Petrels (ACAP; Lewison and Crowder, 2003; Phillips et al., 2016; Dias et al., 2019), while short-tailed albatrosses are also protected by the Endangered Species Act (ESA) in the United States (US). In the North Pacific, albatross bycatch rates were historically high in several fisheries, including US longline fleets, until the introduction of suite of mitigation measures in the early 2000s, which led to massive reductions in mortality, from tens of thousands to only hundreds of birds per year (Gilman et al., 2008; Melvin et al., 2011, 2019). Since the late 2000s, tuna Regional Fisheries Management Organizations (tRFMOs) have mandated the use of best-practice mitigation in pelagic longline fisheries, including use of streamer lines, night setting and line weighting. However, in many fleets, less than 5% of fishing sets are monitored, while many are not routinely monitored in all years (Phillips, 2013). Hence, there is often poor knowledge of where and when bycatch occurs, which fleets and vessels are responsible and whether they are appropriately using bycatch mitigation.

Given the logistical and political challenges and costs associated with collecting fisheries-dependent data, there is increasing emphasis on filling data gaps through alternative, fisheries-independent risk assessments (Clay et al., 2019; Good et al., 2023, 2024). Past research has shown that the three albatross species have wide-ranging distributions across the North Pacific and

encounter and interact with a range of fisheries, predominantly pelagic and demersal longline and trawl (Hyrenbach and Dotson, 2003; Suryan et al., 2007; Fischer et al., 2009; Žydelis et al., 2011; Guy et al., 2013; Orben et al., 2021). To be able to sufficiently identify gaps in monitoring and develop targeted management interventions at the scale of RFMO areas of competency, there is need for standardized assessments of risk at ocean basin scales.

Here, we collate albatross tracking, oceanographic and fishing effort data to dynamically predict year-round distributions of North Pacific albatross populations and identify bycatch risk hotspots and the fishing fleets responsible. Specifically, we aimed to investigate 1) when and where albatross bycatch is most likely to occur, and 2) the fleets and flag states responsible for the highest risk of interactions.

2. Materials and Methods

2.1. Tracking data collection and processing

All available tracking data were collated for the three North Pacific albatrosses and were requested through direct email contact with researchers or through the BirdLife International Seabird Tracking Database (www.seabirdtracking.org). We collated and standardized datasets from all tracked populations, breeding stages (incubation, brood, post-brood and non-breeding) and device types (GPS, PTT or geolocator) for the three species.

We plotted all GPS and PTT tracks and manually removed obviously erroneous locations. Geolocator tracks were estimated based on the timings of sunrise and sunset from light data using established routines, incorporating sea surface temperature (SST) information from tags with remotely-sensed maps to correct latitudes (for further details see Young et al., 2009; Jordan et al., 2022). Erroneous locations occurring two to three weeks either side of the spring and autumn equinox were removed. We took a conservative approach to further remove outliers beyond species' ranges which may lead to exaggerated bycatch risk estimates (e.g. in areas with high fishing intensity but low albatross usage). For black-footed and Laysan albatrosses, we calculated the 99% kernel utilization distribution (UD) isopleth based on all geolocator locations using the R package *adehabitatHR* (Calenge, 2006) and removed locations occurring outside this polygon.

We used the package *track2KBA* (Beal et al., 2021b) to split GPS and PTT tracks into discrete foraging trips, defined as periods of a minimum duration spent outside a spatial buffer around the breeding colony. For each population and breeding stage, we inspected the data and selected appropriate buffers that would exclude locations in the vicinity of the colony and remove incomplete trips. We used the package *foieGras* (Jonsen et al., 2020) to regularize tracks and remove erroneous locations based on a speed filter (90 km/hr). We selected an interpolated sampling interval of four hours for trips during breeding and an interval of twelve hours for short-tailed albatross PTT tracks, the latter to match the temporal resolution of the non-breeding geolocator datasets.

2.2. Species distribution models

Given that birds were tracked over a 20-year period (1998-2018), we built species distribution models (SDMs) to allow us to establish species-environment relationships and predict distributions across comparable time periods. We incorporated oceanographic variables known to influence albatross distributions as predictors in models (Hyrenbach et al., 2002; Suryan et al., 2006; Kappes et al., 2010; Žydelis et al., 2011). Daily dynamic environmental variables were acquired from Copernicus Marine Environmental Monitoring Service (https://marine.copernicus.eu/) and combined with topographic variables and distance from

colony (for breeding data). See Welch et al. (2023) for details on variables and their sources.

We fit species distribution models using boosted regression trees (BRTs) due to their high predictive capability, fast computation time, and ability to fit non-linear relationships and handle collinearity among covariates. We generated pseudo-absences using random background selection at a ratio of 1:5 presences:absences. For breeding datasets, we randomly created absences for each colony within a buffer of the maximum range recorded for that species and breeding stage, which had been cropped by a land polygon to remove points occurring on land. For non-breeding datasets, we randomly created absences within a minimum convex polygon, which had been expanded by 200 km to account for geolocator error (Phillips et al., 2004) removing points occurring on land. Presence and pseudo-absence data were matched to environmental datasets in space and time, and BRTs with a binomial distribution were run for each species, population, and breeding stage. BRTs were built with a bag fraction of 0.6, a tree complexity of three and a learning rate between 0.0001 and 0.0001, to ensure that at least 2,000 trees were fit to each model.

Initial plotting of SDM outputs revealed that distance to colony had a strong effect for breeding models but that predictions were sensitive to the non-linear effect of distance from colony. To generate predictions that were more biologically meaningful and less sensitive to overfitting, we used the methodology of Hindell et al. (2020) and ran BRTs without distance variables. Instead, we created an accessibility layer for each population and breeding stage, and weighted model predictions for each location according to its accessibility from the breeding colony. Accessibility was modelled using a binomial distribution, in terms of the ratio of presences to absences, with distance to colony as a smoothed, monotonic decreasing constraint.

We evaluated the predictive performance of SDMs using the Area Under the Receiver Operator Characteristic Curve (AUC) metric, whereby values between 0.8 and 0.9, and 0.9 and 1.0, represent good and very good performance, respectively. We used two validation methods to assess performance: firstly, we trained models on a random subset of 70% of the data and tested it on the remaining 30%, iteratively 10 times (leave-out-70/30); secondly, for datasets for which we had two or more years of data, we trained on all years but one, and tested on the remaining year (leave-out-year), to test sensitivity of models to differences among tracking years.

Predictions were made for each day across a five-year period (2016-2020) corresponding to the availability of fishing effort data (below), within the spatial constraints of the training data. Daily predictions were averaged for each dataset and month and cropped using the threshold function in the *dismo* package (Hijmans et al., 2023) to remove "unsuitable" habitat. We weighted each probability of occurrence grid such that the sum of all values scaled to 1, to broadly match the structure of a utilization distribution (UD) grid.

2.3. *Weighting distributions according to phenology*

We incorporated data on the timing of major events across the albatross annual cycle to weight model predictions and create monthly maps of predicted probability of presence at a population level, using an approach similar to Clay et al. (2019) and Carneiro et al. (2020). Data on the average timing of 1) return to the colony after non-breeding migration, 2) egg laying, 3) chick hatching, 4) end of chick brood and 5) departure of breeding adults from the colony, were obtained from the literature or from direct contact with data providers. As data were not available for all populations, we assumed phenology was the same for all populations of each species. The average timings were used to create weightings for each month, representing the proportion of that month covered by the four major breeding stages: incubation, brood, post-brood and non-breeding. For example, the average hatching date for Laysan albatrosses is 20 January and so the predicted probability of presence grid based on the incubation SDM was given a weighting of 0.65 (20 out of 31 days), while the probability of presence grid based on the brood SDM was given a weighting of

0.35 (11 out of 31 days). This process was repeated for each species, population and month. If a breeding stage was missing for a given population, that time period was not considered in analyses. We considered distributions during the pre-laying exodus period to be the same as during incubation (Clay et al., 2019).

2.4. *Fishing effort data and overlap analyses*

We obtained Automated Identification System (AIS) fishing effort data v. 2 from Global Fishing Watch (https://globalfishingwatch.org/data-download/datasets/public-fishing-effort) for the period 2016-2020 at a 0.01° resolution. GFW combines public vessel registries and machine learning to identify fishing vessels and detect when they are actively fishing (Kroodsma et al. 2018). Data were resampled to a 2° resolution and effort (the number of fishing hours) in each cell was summed at a monthly level for each gear type and flag state.

We calculated monthly overlap per grid cell — an index of potential bycatch risk — as the predicted probability of albatross presence multiplied by the number of fishing hours (e.g. Jiménez et al., 2016; Clay et al., 2019; Carneiro et al., 2020), separately for each flag state. We also summarized overlap within Exclusive Economic Zones (EEZs; 200 nm from the coast) versus in the High Seas. Monthly distribution grids were overlaid with shapefiles of country land borders and EEZs (v. 11; from https://www.marineregions.org/downloads.php). Here national jurisdictions are areas of EEZs each country including overseas dependencies and disputed territories (Beal et al., 2021a).

3. Results and Discussion

Overall, we collated 1,243 tracks from eleven populations of the three species, including 428 tracks from four populations of black-footed albatrosses (at Torishima, Kure, Midway and Tern), 708 tracks from six populations of Laysan albatrosses (at Kure, Midway, Tern, Kaua'i, O'ahu and Guadalupe), and 107 track from short-tailed albatrosses at Torishima (Table 1). The populations represent around 51%, 78% and >85% of global breeding populations of the three species, respectively.

Through compiling the largest-ever database of albatross tracks in the North Pacific, building on previous studies (e.g. Suryan et al., 2007; Žydelis et al., 2011; Orben et al., 2021; Jordan et al., 2022) we show that the foraging distributions and exposure to fisheries are both species- and population-specific (Figure 1). short-tailed albatrosses that breed in Japan forage along the Japanese coast and along the Aleutian Island chain in Alaska; Laysan albatrosses forage throughout the North Pacific and into the California Current; and black-footed albatrosses have a more sub-tropical distribution, but some populations forage in the northern California Current and Gulf of Alaska. The performance of species distribution models was very high for all species, especially for those based on GPS or PTT datasets (>0.96 for all species based on leave-out-70/30) (Table 2). Performance was lower for models based on geolocator data for Laysan and black-footed albatrosses (0.80 and 0.82 respectively) but still good. While AUC scores were slightly lower for leave-out-year validation, they were still very high for GPS and PTT datasets (>0.92 for all species) and moderate-to-high for geolocator datasets (0.80 and 0.77 for Laysan and black-footed albatrosses), indicating that SDMs still performed well when predicted onto different years of tracking data. As such, we conclude our models were suitable for predicting at-sea distributions and assessing coarse-scale risk outside the temporal range of the tracking data.

We identified five bycatch risk hotspots for pelagic longline fisheries (Figure 2), many of which were shared among the three species. Risk was highest for black-footed and Laysan albatrosses 1) to the northeast of the main Hawaiian Islands and 2) to the northwest of the northwestern

Hawaiian Islands, and for black-footed and short-tailed albatrosses 3) from Torishima up to the east coast of Honshu (Japan), and for Laysan albatrosses also 4) in a High Seas area of northwest Pacific east of Japan and 5) south of the main Hawaiian Islands. The majority (mean = 88%) of risk occurred in the High Seas, with values above 85% for black-footed and Laysan Albatross populations from the northwestern Hawaiian Islands (Kure, Midway and Tern) (Figure 3a). For both Torishima populations, most (78% and 99% for short-tailed and black-footed albatrosses, respectively) overlap with pelagic longline fisheries occurred within the EEZ of Japan, while for Laysan albatrosses from the main Hawaiian Islands (Kaua'i and O'ahu), a substantial proportion of overlap occurred within the US EEZ (85% and 27%, respectively).

Fleets operated by Japan, Taiwan and the US contributed to 91% of total risk. Broadly across the year, risk from pelagic longline fisheries was highest during the breeding season (November-May). Though, the specific months with elevated risk varied according to flag state (Figure 4a); there was elevated risk from US fleets during November to May and from Japanese and Taiwanese fleets during May to November, except for short-tailed albatrosses, for which risk was highest from Japanese fleets during October to May. There was also a distinct longitudinal pattern in bycatch risk, such that risk scores for western populations (Torishima, Kure and Midway) were more likely to be dominated by the fleets of Japan and Taiwan, whereas risk scores for eastern populations (Tern, Kaua'I and O'ahu) were dominated by the US.

Overall, we show that a large proportion of bycatch risk from pelagic longline fisheries occurs in the High Seas of northwest Pacific, where less than 5% of vessels are monitored and use of best-practice bycatch mitigation (such as night setting, line weighting, use of streamer lines or hook-shielding devices) varies (Huang and Yeh, 2011; Sato et al., 2022). Additionally, given that US fisheries only contributed to around a third 32%), of overall risk, our findings suggest that recent bycatch reductions in US-managed fisheries (specifically in Hawai'i and Alaska; Gilman et al., 2008; Melvin et al., 2019) which have relatively high observer coverage (50-100%, depending on the fleet; e.g. NMFS 2023), may be insufficient to manage total risk for albatross populations, particularly northwestern populations. While there should be continued roll-out of streamer lines in the Hawai'i deep-set fleet, we also recommend that fishing fleets outside of US waters improve bycatch monitoring (including electronic monitoring) and use of best-practice mitigation. Specifically, our findings highlight the pelagic longline fleets of Taiwan and Japan (particularly the coastal and smaller offshore fleets), as priorities for further research and management interventions. Regardless, increased adoption of best-practice mitigation measures and penalties for non-compliance across all fishing fleets would reduce future conflicts between fisheries and albatrosses.

Acknowledgements

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Table 1. Summary of tracking data according to species and population.

Species	Region	Population	% global pop.	Breed stages	N. tracks
Laysan albatross	NW Hawaiian Is.	Kure (Mokupāpapa)	4.6	All	63
		Midway (Pihemanu)	72.8	All	105
		Tern (Kānemiloha'i	0.4	All	190
	Main Hawaiian Is.	Kaua'i (Waipake & Nai Aina Kai)	<0.1	All	192
		O'ahu	<0.1	Post-brood	84
	Mexico Offshore Is.	Guadalupe	0.2	All	266
Black-footed albatross	Japan Offshore Is.	Torishima	2.9	Incubation, brood, post-brood	21
	NW Hawaiian Is.	Kure (Mokupāpapa)	4.9	Brood, post-brood	158
		Midway (Pihemanu)	36.5	Post-brood	79
		Tern (Kānemiloha'i)	7.1	All	170
Short-tailed albatross	Japan Offshore Is.	Torishima	85%	All	107

"All" under the Breed stage column represents that there were sufficient data for incubating, chick-rearing and non-breeding birds.

Table 2. Summary of species distribution model performance based on the Area Under the Receiver Operator Curve (AUC) statistic for each species, device type and model validation method. The median AUC score provided for each method with the range in parentheses. Leave-out-70/30 indicates where the model was trained on a random subset of 70% of the data and tested on the remaining 30%; Leave-out-year represents where the model was iteratively trained on all but one year of data and tested on the remaining year.

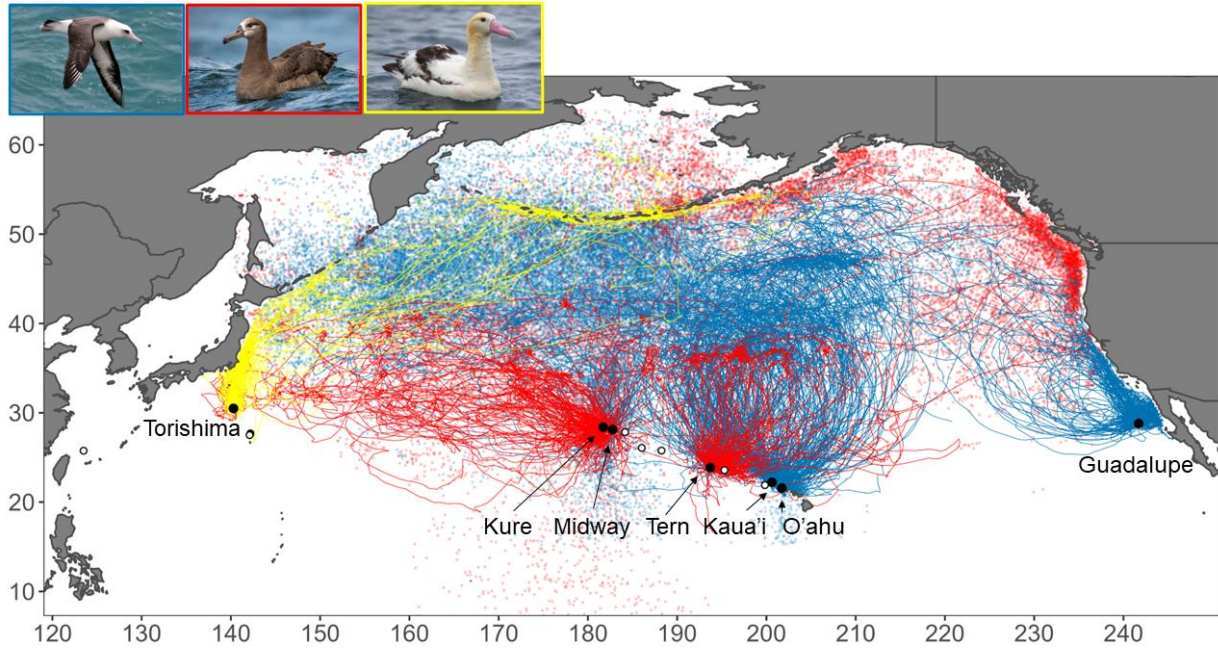| Validation method	Species	N datasets	AUC score (performance)	
			GPS/PTT	Geolocator
Leave-out-70/30	Laysan albatross	24	0.97 (0.94-0.99)	0.80 (0.68-0.86)
	Black-footed albatross	11	0.98 (0.95-0.99)	0.82 (0.80-0.84)
	Short-tailed albatross	4	0.96 (0.91-0.99)	–
Leave-out-year	Laysan albatross	10	0.95 (0.89-0.98)	0.80 (0.79-0.82)
	Black-footed albatross	6	0.95 (0.91-0.97)	0.77 (0.75-0.78)
	Short-tailed albatross	2	0.92 (0.88-0.97)	–

Figure 1. Compilation of more than 1,200 foraging tracks from 11 populations of three albatross species in the North Pacific Ocean. Blue tracks represent Laysan albatrosses, red tracks represent black-footed albatrosses and yellow tracks represent short-tailed albatrosses.
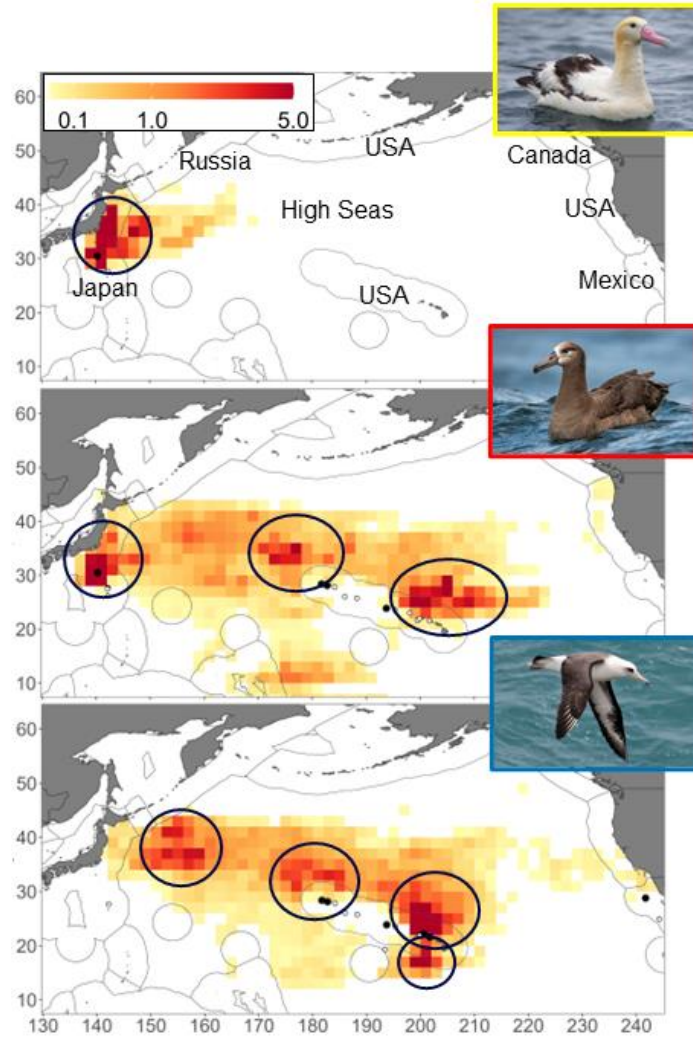
Figure 2. Bycatch risk hotspots for short-tailed (top row), black-footed (middle row) and Laysan (bottom row) albatrosses in the North Pacific Ocean with pelagic longline fisheries. The color gradient indicates increasing risk (red represents the highest risk and light yellow represents the lowest risk) and hotspot areas are shown with black circles.
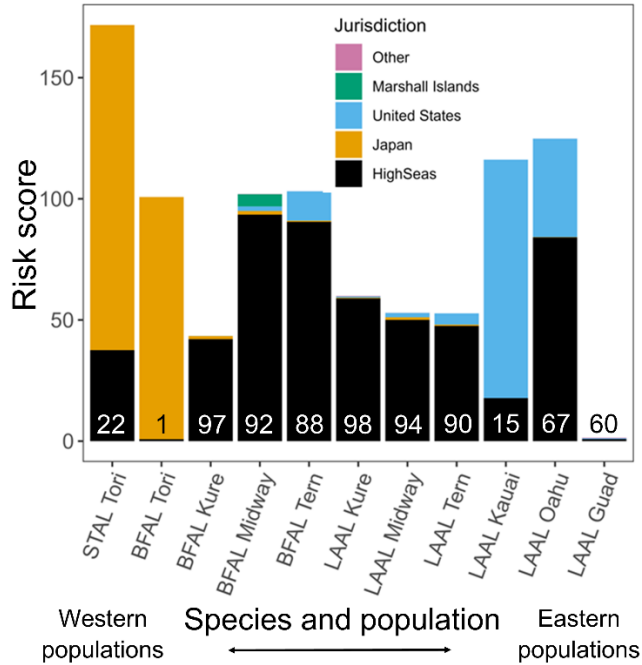
Figure 3. Bycatch risk from pelagic longline fisheries according to jurisdiction (Exclusive Economic Zone [EEZ] or High Seas) and population (bar). The average bycatch risk across the year is shown for each species and population, with westernmost populations on the left and easternmost populations on the right. Bars are filled according to jurisdiction, with the percentage of risk within the High Seas for each population specifically labeled at the bottom of each bar. STAL = short-tailed albatross; BFAL = black-footed albatross; LAAL = Laysan albatross; Tori = Torishima Island (Japan), Guad = Isla Guadalupe (Mexico).
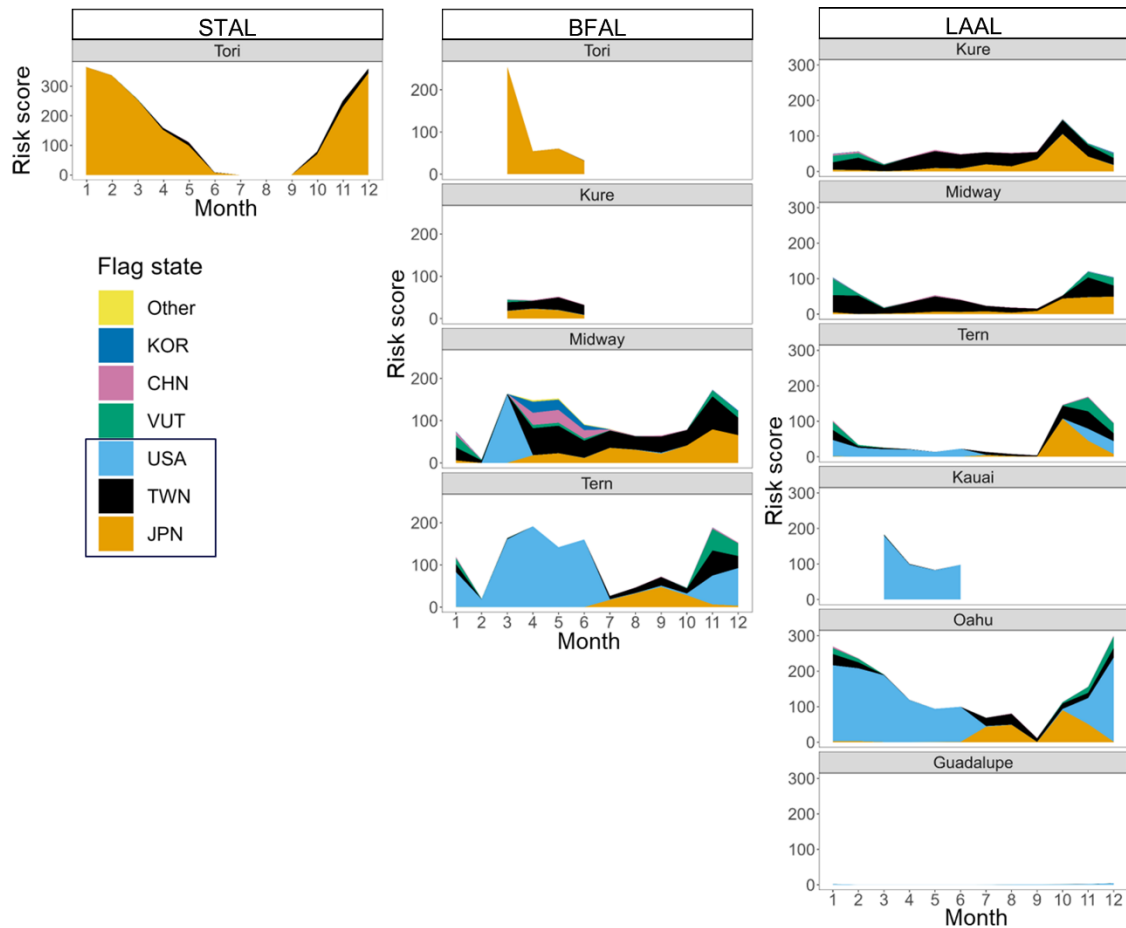
Figure 4. Bycatch risk according to species, population, month and flag state for pelagic longline fisheries. For each species (column) and population (row), the total bycatch risk in each month is shown, with the contribution of each flag state shown by a separate colour. Populations are ordered from the westernmost (top row) to the easternmost (bottom row) for each species. The black box in the legend indicates the three flag states with the highest cumulative bycatch risk. STAL = short-tailed albatross; BFAL = black-footed albatross; LAAL = Laysan albatross; Tori = Torishima. Flag states: CHN = China; JPN = Japan; KOR = South Korea; Other = all other flag states combined; TWN = Taiwan; USA = United States of America; VUT = Vanuatu.